

Inflection point in running kinetic term inflation

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Abstract

In this work, we consider inflection point inflation in the framework of running kinetic term inflation in supergravity. We study the inflationary dynamics and show that the predicted value of the scalar spectral index and tensor-to-scalar ratio can lie within the 1σ confidence region allowed by the result of Planck 2015.

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I. INTRODUCTION

Inflation was proposed to address a series of questions, such as horizon problem, flatness problem, monopole problems and so on. Moreover cosmological inflation is now getting established by all observational data such as the WMAP [1] and Planck space missions [2]. Last year, the full-mission Planck observations of the cosmic microwave background radiation anisotropies constrain the spectral index of curvature perturbations and the tensor-to-scalar ratio to be $n_s = 0.9655 \pm 0.0062$ and $r_{0.002} < 0.10$ at 95% confidence level [2], respectively, which will narrow down some inflation models.

Among various ways of inflation models building, an interesting framework is embed the inflationary models into a more fundamental theory of quantum gravity, such as supergravity. However, most of the old inflation models constructed in supergravity [3–5] suffer from the η problem [6]: The F-term potential is proportional to an exponent factor $e^{|\phi|^2}$, which gives a contribution to one of the slow-roll parameter η , and breaks the slow-roll condition. This problem can be solved by several methods [7–10]. One of the methods is to add a shift-symmetric $\phi \rightarrow \phi + C$ to the Kähler potential $K(\phi - \phi^\dagger)$ [11–15]. So the inflaton will not appear in the Kähler potential, then the exponent factor disappear and guarantee the flatness of the potential. In this case, one can get the normal chaotic inflation with a power-law potential $V(\phi) \propto \phi^n$.

In Ref.[16–18], the author extend the Nambu-Goldstone-like shift symmetry of chiral superfield ϕ to a generalized form $\phi^n \rightarrow \phi^n + C$, then the Kähler potential is a function of $(\phi^n - \phi^{n\dagger})$. In order to get a reasonable potential, one should consider small shift symmetry breaking terms $\kappa|\phi|^2$ in the Kähler potential and $\lambda\phi^m X$ in the superpotential respectively, with $\kappa, \lambda \ll 1$, and X is an extra superfield. Then one can get a fraction-power scalar potential $V(\phi) \propto \phi^{m/n}$, the scalar spectral index n_s and tensor-to-scalar ratio r can be approximate as $n_s = 1 - (1 + \frac{m}{n})\frac{1}{N}$, $r = \frac{8m}{n}\frac{1}{N}$ [17]. Since the coefficient of the kinetic term in this model is field-dependent: $(\kappa + n^2|\phi|^{(2n-2)})\partial_\mu\phi\partial^\mu\phi^\dagger$, it is so called running kinetic term inflation.

The inflection point inflation in the framework of MSSM was for the first time realized by the gauge invariant flat directions udd or LLe [19], and developed in [20–23]. In Ref.[24]

we constructed an inflection point inflationary model with a single chiral superfield, which are consistent with the Planck 2015 result. And after inflation, the model has a non-SUSY de-Sitter vacuum responsible for the recent accelerated expansion of the Universe.

In this paper, we will consider the possibility to construct an inflection point inflationary model with a generalized shift symmetry. We first calculate the general form of the scalar potential with polynomial superpotential in the framework of running kinetic term inflation, then focus on a polynomial superpotential of the form $W = X(\lambda_p \phi^p + \lambda_q e^{i\theta} \phi^q)$ and setup the inflection point inflationary model. We study the inflationary dynamics and show that the predicted value of the scalar spectral and tensor-to-ratio are consistent with the result of Planck 2015 at the 95% confidence level. After the end of inflation, the inflaton starts to oscillate around the origin, and then decays into SM particles to reheat the Universe.

The outline of this paper is as follows: In the next section, we give the general form of the scalar potential with polynomial superpotential. In Section 3, we focus on the polynomial superpotential having two terms and setup the inflection point inflationary model. In Section 4, we discuss the inflationary dynamics of the model.

II. POLYNOMIAL SUPERPOTENTIAL WITH RUNNING KINETIC TERM

In this section, we will calculate the scalar potential of polynomial superpotential in the framework of running kinetic term inflation model in supergravity. In such model, the Kähler potential satisfy the generalized shift symmetry of chiral superfield ϕ :

$$\phi^n \rightarrow \phi^n + C, \quad (1)$$

thus it must be a function of $i\chi \equiv (\phi^n - \phi^{n\dagger})$:

$$K = \sum_{l=1} \frac{c_l}{l} (\phi^n - \phi^{n\dagger})^l = ic_1 (\phi^n - \phi^{n\dagger}) - \frac{1}{2} (\phi^n - \phi^{n\dagger})^2 + \dots \quad (2)$$

with coefficient c_l is a number of the order of unity. During inflation, we can prove that χ is stabilized at the minimum, so the terms with $l \geq 3$ does not change the form of the kinetic term significantly, thus we neglect them[16]. And for $l \leq 2$, χ is stabilized at $\chi_{min} \simeq c_1$ during inflation.

In order to give a successful inflation, a small shift symmetry breaking term are necessary for the Kähler potential:

$$\Delta K = \kappa |\phi|^2, \quad (3)$$

with $0 < \kappa \ll 1$.

Different from Ref.[17], we assumed the superpotential to be a more general form [15, 25–28]

$$W = X \left(\sum_{m=0} \lambda_m \phi^m \right) + W_0. \quad (4)$$

Here $\lambda_m \ll 1$, and X is an extra chiral superfield, which is assumed to be stabilized at $X = 0$ by higher order terms in the Kähler potential. And $|W_0| \simeq m_{3/2}$ with $m_{3/2}$ is the gravitino mass, which is assumed much smaller than the Hubble parameter during inflation, so it can be dropped in the discussion of the inflationary dynamics.

So the total Kähler potential are

$$K = \kappa |\phi|^2 + c_1 (\phi^n - \phi^{n\dagger}) - \frac{1}{2} (\phi^n - \phi^{n\dagger})^2 + |X|^2 \dots \quad (5)$$

where the dots denote the higher order stabilized term of X .

The effective Lagrangian for the scalar ϕ is determined by superpotential W as well as Kähler potential, which is given by

$$\begin{aligned} L &= -K^{\phi\phi^\dagger} \partial_\mu \phi \partial^\mu \phi^\dagger - V \\ &= (\kappa + n^2 |\phi|^{(2n-2)}) \partial_\mu \phi \partial^\mu \phi^\dagger - V, \end{aligned} \quad (6)$$

and the scalar potential of the inflaton can be calculated by

$$\begin{aligned} V &= e^K \left[D_\phi W (K^{-1})^{\phi\phi^\dagger} (D_\phi W)^* - 3|W|^2 \right] \\ &= e^{\kappa |\phi|^2 + c_1 (\phi^n - \phi^{n\dagger}) - \frac{1}{2} (\phi^n - \phi^{n\dagger})^2} \left(\sum_m \lambda_m |\phi|^m \right)^2, \end{aligned} \quad (7)$$

where

$$D_\phi W = \partial_\phi W + (\partial_\phi K) W, \quad (8)$$

and $(K^{-1})^{\phi\phi^\dagger}$ is the inverse of the Kähler metric

$$K^{\phi\phi^\dagger} = \frac{\partial^2 K}{\partial \phi \partial \phi^\dagger} \quad (9)$$

For $(\kappa/n^2)^{1/(2n-2)} \ll |\phi| \ll \kappa^{-1/2}$, the κ -term can be neglected, so we can define $\hat{\phi} \equiv \phi^n$, which means that $\hat{\phi}$ is invariant under a Nambu-Goldstone like shift symmetry, and then the Lagrangian (6) can be approximated by

$$\begin{aligned} L &= \partial_\mu \hat{\phi} \partial^\mu \hat{\phi}^\dagger - e^{-\frac{|c_1|^2}{2}} \left(\sum_m \lambda_m |\hat{\phi}|^{m/n} \right)^2 \\ &= \partial_\mu \hat{\phi} \partial^\mu \hat{\phi}^\dagger - \left(\sum_m \hat{\lambda}_m |\hat{\phi}|^{m/n} \right)^2, \end{aligned} \quad (10)$$

where we have used $i\chi \equiv (\phi^n - \phi^{n\dagger}) = ic_1$, $\hat{\lambda}_m \equiv e^{-\frac{|c_1|^2}{4}} \lambda_m$.

Because of the shift symmetry, the real component of $\hat{\phi}$ does not appear in the Kähler potential, so the potential is considerably flat along the real direction and thus becomes an inflaton candidate. the imaginary component acquires a mass heavier than the Hubble scale and is stabilized at the minimum during inflation. Therefore, we can set $\hat{\phi} \equiv (\varphi + i\chi)/\sqrt{2} = \varphi/\sqrt{2} + ic_1/2$ and obtain the scalar potential of φ , which has the form

$$V = \left[\sum_{m=0} \hat{\lambda}_m \left(\frac{\varphi}{\sqrt{2}} \right)^{\frac{m}{n}} \right]^2. \quad (11)$$

III. SETUP OF THE INFLECTION POINT INFLATION

In order to construct an inflection point inflationary model, we will focus on a polynomial superpotential having two terms

$$W = X(\lambda_p \phi^p + \lambda_q e^{i\theta} \phi^q), \quad (12)$$

with the powers $q > p \geq 1$ are integer, and the coefficient λ_p, λ_q is positive without loss of generality, θ is the phase of the second term.

Using Eq.(11), the scalar potential corresponding to the superpotential (12) can be written by

$$\begin{aligned} V &= \left[\hat{\lambda}_p \left(\frac{\varphi}{\sqrt{2}} \right)^{\frac{p}{n}} + \hat{\lambda}_q e^{i\theta} \left(\frac{\varphi}{\sqrt{2}} \right)^{\frac{q}{n}} \right]^2 \\ &= \hat{\lambda}_p^2 \left(\frac{\varphi}{\sqrt{2}} \right)^{\frac{2p}{n}} \left[1 + 2\xi \cos \theta \left(\frac{\varphi}{\sqrt{2}} \right)^{\frac{q-p}{n}} + \xi^2 \left(\frac{\varphi}{\sqrt{2}} \right)^{\frac{2(q-p)}{n}} \right], \end{aligned} \quad (13)$$

where $\hat{\lambda}_{p,q} \equiv e^{-\frac{|c_1|^2}{4}} \lambda_{p,q}$ and $\xi = |\hat{\lambda}_q/\hat{\lambda}_p| = |\lambda_q/\lambda_p|$. The curve of the potential is shown in Fig.1.

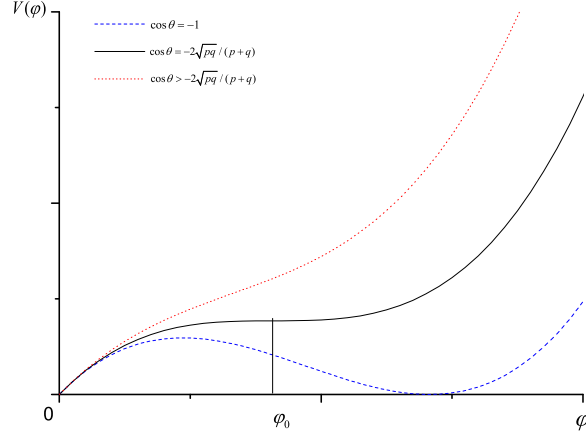


FIG. 1. The inflation potential $V(\varphi)$ with $\cos \theta = -1$ (dash line), $\cos \theta = -2\sqrt{pq}/(p+q)$ (solid line), $\cos \theta > -2\sqrt{pq}/(p+q)$ (dot line), respectively.

We could see that if $\cos \theta = -1$, there are one minimum at $\varphi = \sqrt{2}(\frac{p}{\xi q})^{\frac{n}{q-p}}$ and one minimum or zero value at $\varphi = 0$ respectively, which is shown in Fig.1(dash line). As $\cos \theta$ increase, the minimum at $\varphi = \sqrt{2}(\frac{p}{\xi q})^{\frac{n}{q-p}}$ is uplift. In this case, the initial value of the inflation field should below the local maximum, otherwise the inflaton will be trapped in the false vacuum.

An interest case is that if the parameters θ satisfies the relation

$$\cos \theta = -\frac{2\sqrt{pq}}{p+q} \quad (14)$$

the local maximum and the second minimum will be the same at point $\varphi_0 = \sqrt{2}\left(\frac{1}{\xi}\sqrt{\frac{p}{q}}\right)^{\frac{n}{q-p}}$, and the false vacuum disappears(solid line), this point is called inflection point. At this point, the inflation potential is

$$V(\varphi_0) = \hat{\lambda}_p^2 \left(\frac{p}{q} + \frac{4p}{p+q} + 1 \right) \left(\frac{p}{\xi^2 q} \right)^{\frac{p}{q-p}}, \quad (15)$$

and both the first and second derivatives of V vanish at φ_0 . It's worth mentioning that this potential is independent of n , so for different n , the potential at inflection point are almost the same. And we will see shortly that since there is a flat plateau at the inflection point

φ_0 , the predicted spectral index as well as the tensor-to-scalar ratio can lie within the 1σ confident region allowed by Planck 2015.

When $\cos\theta > -\frac{2\sqrt{pq}}{p+q}$, then the flat plateau disappear, and power law inflation model will be reproduced(dot line).

It is worth mentioning that the potential near the origin is an odd function for some choice of parameters, which will cause undesirable behavior after inflation. It doesn't matter since when the scalar field $\varphi < \sqrt{2}(\kappa/n^2)^{n/(2n-2)}$, the first term of the kinetic term κ in (6) become important, so we couldn't drop it, and the scalar ϕ becomes the dynamical variable. Then the potential in this region is not as in Fig.1, which will have the form $(\sum_m \lambda_m |\phi|^m)^2$. And as ϕ decrease, the soft SUSY breaking mass term $m_\phi |\phi|^2$ will dominates the potential[17], so the scalar will oscillate around the origin and reheat the Universe.

In this paper we focus on the inflation potential with inflection point. Since the parameter θ satisfy the relation(14), so for a given n, p and q , there are only two free parameters $\hat{\lambda}_p$ and ξ . The inflation potential (13) becomes

$$V(\varphi) = \hat{\lambda}_p^2 \left(\frac{\varphi}{\sqrt{2}} \right)^{\frac{2p}{n}} \left[1 - 4\xi \frac{\sqrt{pq}}{p+q} \left(\frac{\varphi}{\sqrt{2}} \right)^{\frac{q-p}{n}} + \xi^2 \left(\frac{\varphi}{\sqrt{2}} \right)^{\frac{2(q-p)}{n}} \right]. \quad (16)$$

IV. SLOW-ROLL INFLATION

The slow-roll parameters ϵ and η are defined by

$$\begin{aligned} \epsilon &\equiv \frac{1}{2} \left(\frac{V'(\varphi)}{V(\varphi)} \right)^2, \\ \eta &\equiv \frac{V''(\varphi)}{V(\varphi)}. \end{aligned} \quad (17)$$

To first order in the slow-roll approximation, the scalar spectral index n_s and tensor-to-scalar ratio r are expressed in terms of the slow-roll parameters:

$$\begin{aligned} n_s &\simeq 1 - 6\epsilon + 2\eta, \\ r &\simeq 16\epsilon. \end{aligned} \quad (18)$$

The number of e -folding during inflation can be written by

$$N = \int_{\varphi_f}^{\varphi_i} \frac{V}{V'} d\varphi, \quad (19)$$

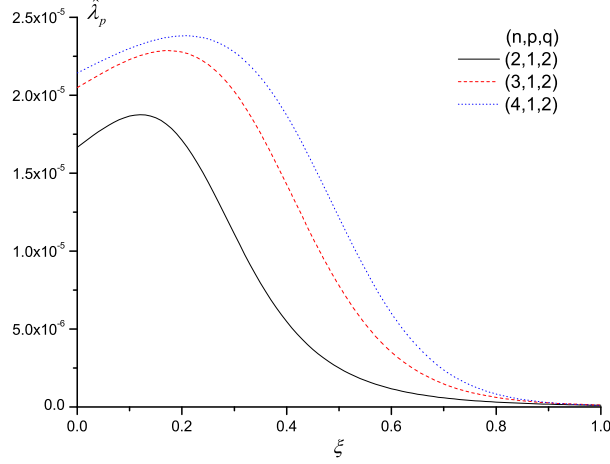


FIG. 2. (color online) The value of $\hat{\lambda}_p$ and ξ for reproducing the Planck observed amplitude of curvature perturbations. With the e-folding number $N = 60$, and p, q are set to be $(1, 2)$. The black solid line, red dash line and blue dot line corresponds to the numerical result with the parameters $n = 2, 3$ and 4 respectively.

and the field value at the end of inflation φ_f is determined by $\text{Max}\{\epsilon(\varphi_f), \eta(\varphi_f)\} = 1$.

The parameter $\hat{\lambda}_p$ is constrained by the amplitude of curvature perturbations:

$$\Delta_R^2 = \frac{V}{24\pi^2\epsilon}. \quad (20)$$

The maximum likelihood value from the Planck 2015 data is $\Delta_R^2(k_0) = 2.19 \times 10^{-9}$, so for a given n, p and q , we can get the relation between $\hat{\lambda}_p$ and ξ . The corresponding figures are shown in Fig. 2, 3, 4 and 5 for different parameters n, p and q and the e-folding number $N = 60$ or 50 respectively.

Fig. 6, 7, 8 and 9 show the $n_s - r$ region predicted by the model for different parameters n, p and q . The contours are the marginalized joint 68% and 95% confidence level regions for n_s and r at the pivot scale $k_* = 0.002 \text{ Mpc}^{-1}$ from the Planck 2015 TT+lowP data. We could see that the curves are consistent with the Planck data. The dots on the line correspond to the case of $\xi = 0$, which is just the case of origin running kinetic term inflationary model with potential $V \propto \varphi^{m/n}$ [17], and as ξ increases, the $n_s - r$ dots go along the curves to the left.

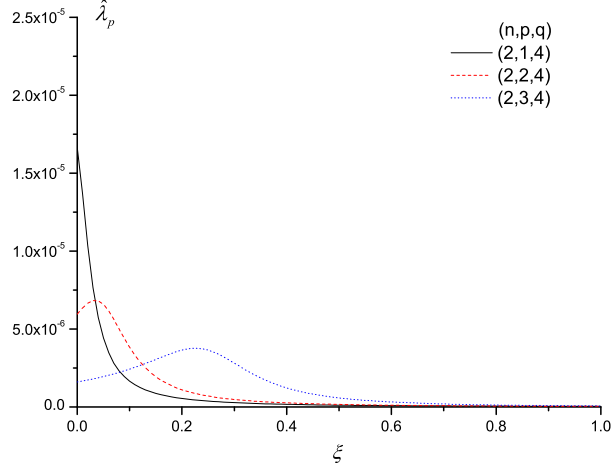


FIG. 3. (color online) The value of $\hat{\lambda}_p$ and ξ for reproducing the Planck observed amplitude of curvature perturbations. With the e-folding number $N = 60$, and n, q are set to be $(2, 4)$. The black solid line, red dash line and blue dot line corresponds to the numerical result with the parameters $p = 1, 2$ and 3 respectively.

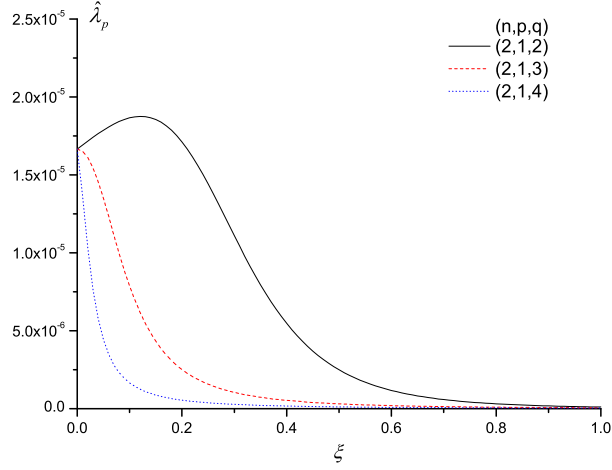


FIG. 4. (color online) The value of $\hat{\lambda}_p$ and ξ for reproducing the Planck observed amplitude of curvature perturbations. With the e-folding number $N = 60$, and n, p are set to be $(2, 1)$. The black solid line, red dash line and blue dot line corresponds to the numerical result with the parameters $q = 2, 3$ and 4 respectively.

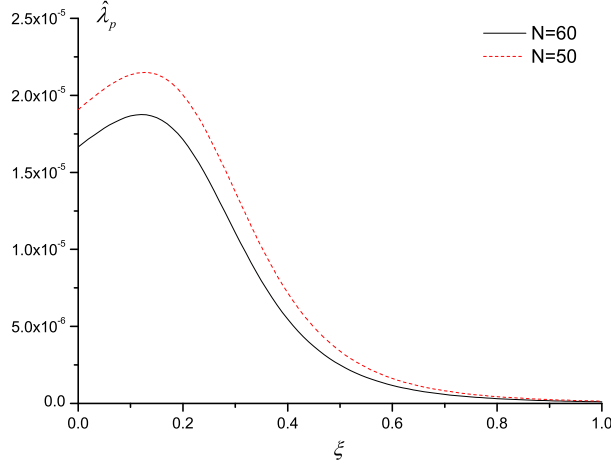


FIG. 5. (color online) The value of $\hat{\lambda}_p$ and ξ for reproducing the Planck observed amplitude of curvature perturbations. And n, p, q are set to be $(2, 1, 2)$. The black solid line and red dash line corresponds to the numerical result with the e-folding number $N = 60$ and $N = 50$ respectively.

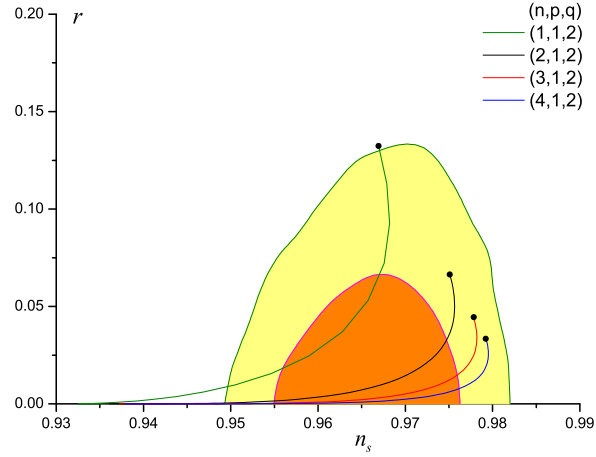


FIG. 6. (color online) The $n_s - r$ region predicted by the model with the e-folding number $N = 60$. The contours are the marginalized joint 68% and 95% confidence level regions for n_s and r at the pivot scale $k_* = 0.002 \text{ Mpc}^{-1}$ from the Planck 2015 TT+lowP data. The parameters p, q are set to be $(1, 2)$, and the power n is taken as $n = 1, 2, 3$ and 4 from top to bottom. The dots on the line correspond to the case of $\xi = 0$.

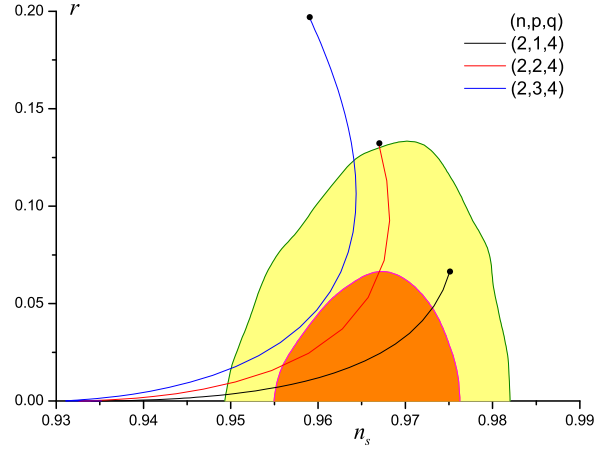


FIG. 7. (color online) The $n_s - r$ region predicted by the model with the e-folding number $N = 60$. The parameters n, p are set to be $(2, 4)$, and the power p is taken as $p = 3, 2, 1$ from top to bottom. The dots on the line correspond to the case of $\xi = 0$.

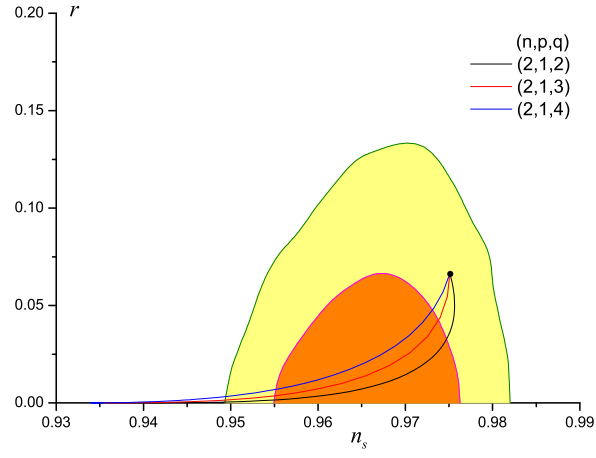


FIG. 8. (color online) The $n_s - r$ region predicted by the model with the e-folding number $N = 60$. The parameters n, p are set to be $(2, 1)$, and the power q is taken as $q = 4, 3, 2$ from top to bottom. The dots on the line correspond to the case of $\xi = 0$.

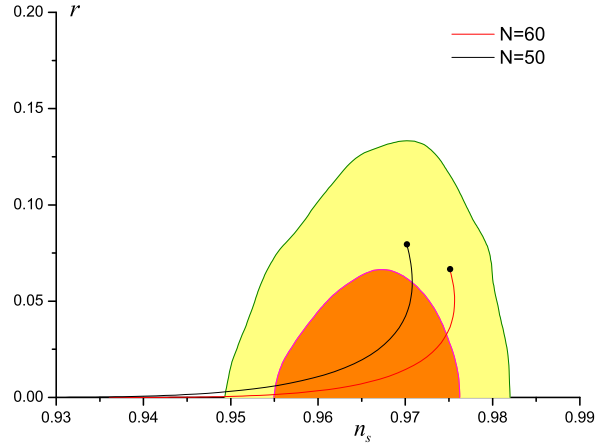


FIG. 9. (color online) The $n_s - r$ region predicted by the model. The parameters n, p, q are set to be (2,1,2). The black line and red line corresponds to the numerical result with the e-folding number $N = 60$ and $N = 50$ respectively.

From Fig.6, we could see that for a given $p = 1$ and $q = 2$, as n increase from 1 to 4, the curves become lower and lower, and become better agreement with the Planck data. Notice that $n = 1$ is just the case of the original inflection point inflation. In Fig.7, we assume the parameters $n = 2, q = 4$, the curves from top to bottom are the power $p = 3, 2, 1$ respectively. In Fig.8, the parameters are assumed $n = 2, p = 1$, the curves from top to bottom are the power $q = 4, 3, 2$ respectively. We could see that the three curves converge to one point, the point is just the case of $\xi = 0$, which is just the prediction of the origin model with the potential $V \propto \varphi^{m/n}$. The two curves in Fig.9 are the case of $N = 60$ (black line) and $N = 50$ (red line) respectively. It can be seen from these figures that the predictions are consistent with the Planck 2015 results.

After the end of inflation, the scalar φ will becomes small, and when $\varphi < \sqrt{2}(\kappa/n^2)^{n/(2n-2)}$, the first term κ in the kinetic term (6) becomes more important, then the scalar ϕ becomes the dynamical variable. In this region the potential will have the form $(\sum_m \lambda_m |\phi|^m)^2$. And as the field ϕ decrease, the soft SUSY breaking mass term $m_\phi |\phi|^2$ will dominates the potential. The inflaton will oscillate around the origin, and then decays into SM particles by

introducing the couplings with Higgs doublets such as $W = \lambda_X X H_u H_d$ or $W = \lambda_\phi \phi H_u H_d$, to reheat the Universe. The reheating process are quite similarly as in Ref.[17].

V. SUMMARY

In this work, the inflection point inflation in the framework of running kinetic term inflation in supergravity has been successfully constructed using the polynomial superpotential having two terms. The inflationary predictions of the model are consistent with the Planck 2015 results. Such predictions in the $n_s - r$ plane are better than the original model with scalar potential $V \propto \phi^{m/n}$. After inflation, the inflaton will oscillate around the origin and then decays into SM particles by introduce some unsuppressed coupling with SM sector, such as Higgs doublets.

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